

# SELECTION AND DESIGN OF COOL STORAGE SYSTEMS

*Brian Silveti, P.E.*  
(201) 569-0420

## ABSTRACT

The major aspects of thermal energy storage system selection and design for commercial cooling installations are discussed and studied. Although primarily directed towards secondary coolant, ice based, phase change storage equipment, the discussions are generally applicable to cooling storage systems of other types. Particular emphasis is placed on the effects that decisions in one area of design will have on others.

## INTRODUCTION

Once the peak cooling load and distribution temperatures are specified in a conventional design, the remaining decisions regarding equipment selection, arrangement and control of the cooling plant are reasonably uncomplicated. When thermal storage is introduced, however, additional considerations must usually be addressed. Although these additional considerations are no more complex than any others in the HVAC design process, it is usually impossible to approach any of them independently, as changes in one area invariably affect the decisions made in others. For instance, if the chiller is located downstream of storage, rather than upstream, its cooling capacity may be reduced while total storage capacity may be increased, requiring a recalculation for both. Additionally, the method of control may have to be adjusted in order to fully exploit the economic benefits of the applicable rate structure. Also, decisions regarding the practical range of supply and return temperatures may be expanded or reduced, influencing the consideration of other heat exchange devices.

## FULL STORAGE

Most of the complications surrounding the selection and design of thermal storage systems are related to multiple chiller

operating conditions and the proper assignment of cooling load to either the storage system or the chiller. These issues do not impact full storage systems. The chiller operates only in an ice-making mode and its operating conditions are as easily defined as in any conventional system. During the cooling period, the storage system is the only active component and proper control is greatly simplified. Moreover, the system components are generally compatible with standard flow rates and temperature differentials. There may be other considerations such as a concurrent cooling load during the ice-making period, or proper interface with a chilled water system through a heat exchanger, but these topics can be completely addressed within the context of partial storage systems.

The most important feature of full storage systems is the impact on the size and cost of the individual components. As will be demonstrated in the selection procedures, a full storage approach can easily more than double both the required chiller and storage capacities over what would be required for a partial storage system. Unless the electrical rate structure severely penalizes peaking demand, initial costs can be difficult to justify without some type of incentive program. Partial storage, on the other hand, is typically installed at costs equivalent to conventional systems.

Otherwise, full storage can be considered as a simpler subset of partial storage design and our focus will be directed toward the partial storage approach, with reference to full storage issues as appropriate.

## **PARTIAL STORAGE EQUIPMENT SELECTION**

### **MINIMUM CHILLER SELECTION**

In a conventional system, the chiller capacity is generally dictated by the peak cooling load of the building, with adjustments made on the basis of preferences regarding redundancy, chiller type and safety margins. For thermal storage systems, the chiller capacity is dependent on the total daily integrated cooling load, rather than the peak cooling load. And, because the designer can choose what portion of the cooling load will be shifted to off-peak operation, only a

minimum sized chiller is defined by the cooling requirements. The designer is free to increase chiller capacities above this value. The amount of required storage can be reduced by operating more chiller kW (tons) during the day, or on-peak demand can be further reduced by increasing the amount of storage, with decreased chiller contribution during the day.

Since the chiller size no longer depends on the peak cooling load, some other relationship is needed to establish the required capacity. Since all of the cooling must originate with the chiller, whether eventually delivered directly by the chiller or through storage, we can simply equate the total chiller contribution to the integrated daily cooling load. Our example will be based on the design day load profile depicted in figure 1. By using a peak load of 1 kW, the resulting chiller capacities can be interpreted as a percentage of peak load. This simplifies the estimation of potential demand savings and relative storage sizing.

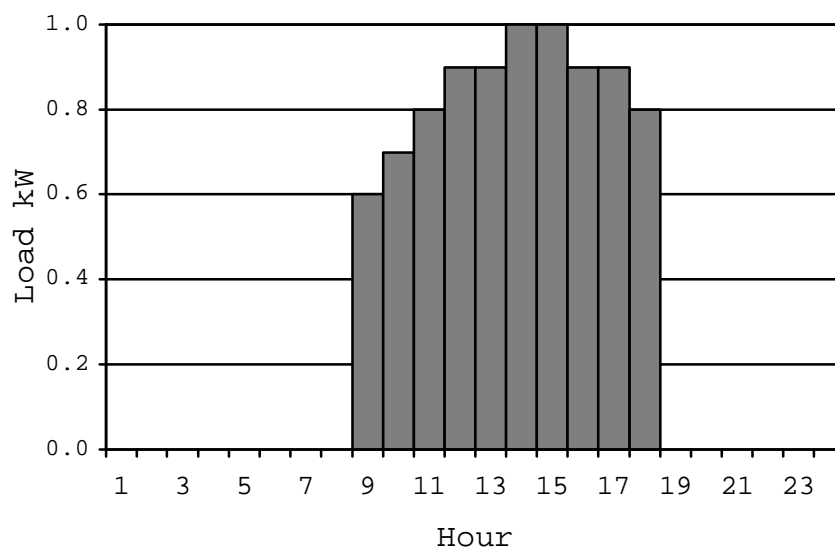


FIGURE 1 - DESIGN DAY LOAD PROFILE

The required chiller capacity is unknown at this point, but the capacities, relative to some standard condition, can easily be identified for each time period. The chiller actually may operate over a range of condenser and evaporator conditions but

these are generally reduced to only two conditions, ice-making and direct cooling. If additional accuracy is desired, the designer needs only to increase the number of terms, each with its own relative chiller capacity.

$$Total\ kWhrs = (Chiller\ kW \times Ice\ cap. \times Ice\ hrs) + (Chiller\ kW \times Day\ cap. \times Day\ hrs)$$

$$Chiller\ kW = \frac{Total\ kWhrs}{(Ice\ cap. \times Ice\ hrs) + (Day\ cap. \times Day\ hrs)} \quad Eq\ 1$$

$$Chiller\ kW = \frac{8.5\ kWhrs}{(.65 \times 14) + (1 \times 10)\ hrs}$$

$$Chiller\ kW = .445\ kW \quad (All\ kW\ are\ thermal)$$

In the example we have chosen the day-time chiller capacity (Day cap) as 1 (100%) and the night-time, ice-making capacity (Ice cap), as .65 (65%). In other words, we expect a 100 kW chiller to provide 100 kW during the day and 65 kW in the ice-making mode. Note that this is a capacity reduction and not an efficiency reduction. Depending on the type of equipment and the ambient temperature drop at night, ice-making efficiencies can equal or exceed those available during the day. These capacity fractions are then multiplied by the number of hours at each condition. A simple rearrangement of the terms will provide the chiller capacity directly, keeping in mind that this is the minimum sized chiller for the conditions evaluated.

Examination of the formulas reveals the aspects of partial storage systems that minimize first cost and make it competitive with conventional systems. First, the chiller is fully loaded throughout the cooling period. Even on a design day, conventional system chillers are rarely loaded to maximum capacity. Second, the addition of an ice-making period, even at reduced capacity, substantially increases the available chiller capacity. It is not unusual to have 18 or 19 full load equivalent chiller operating hours. Also, because the chiller is fully loaded throughout the cooling period, only the variable peak loads must be served from storage.

If we consider for a moment the requirements for a full storage analysis, it is readily seen that the daytime contribution of the chiller becomes zero (0) and the entire cooling load must be provided by a chiller operating at reduced capacity in a more limited period of time. A recalculation, without a daytime chiller contribution (Day hrs=0), results in a chiller of .934 kW that approaches the original conventional chiller size and can easily exceed that value in some cases. The storage capacity, as demonstrated in the next section, will also be dramatically increased. Certainly the on-peak demand is substantially decreased for full storage, but lacking incentives of some type, the time to recover the initial investment often exceeds acceptable limits.

#### STORAGE SELECTION (KWHRS (TON-HOURS))

The required storage capacity, in kWhrs (ton-hrs), is simply equal to the ice-making capacity of the above described chiller and, for the minimum sized chiller, will also be equal to that part of the cooling load not served directly by the chiller during the day.

$$\text{Storage kWhrs} = \text{Chiller kW} \times \text{Icecap} \times \text{Icehrs} \quad \text{Eq 2}$$

$$\text{Storage kWhrs} = \text{Total kWhrs} - (\text{Chiller kW} \times \text{Daycap} \times \text{Dayhrs}) \quad \text{Eq 3}$$

If, for some reason, a chiller larger than the minimum is chosen, the designer has the option of using the increased capacity to build more ice, thereby allowing a reduced chiller contribution during the day. The storage kWhrs (ton-hrs) can increase to as much as the ice-making chiller can produce in the available time (Eq. 2).

Alternatively, the larger chiller can be used to reduce the required storage capacity. The needed ton-hrs are equal to the total on-peak cooling load, less the larger chiller contribution (Eq 3). As the chiller grows beyond the minimum, the difference between the minimum amount of storage needed, and the maximum

that can be used, diverges. Increasing chiller size while decreasing storage capacity has practical limits. As the storage capacity decreases, its ability to absorb all of the chiller output is reduced, driving down the chiller operating temperatures to inefficient and perhaps dangerous levels. Unloading of the chiller is often not an option for several reasons. Centrifugal chillers will be forced closer to their surge limits and the refrigerant metering devices of positive displacement machines can become more unstable with reduced refrigerant flow at ice-making conditions. Where limitations on ice-making capacity are desired, multiple chillers are often recommended. In any case, manufacturers should be contacted if chiller unloading in the ice-making mode is contemplated. The affect of larger alternate chiller sizes can be seen in Table 1.

TABLE 1 STORAGE REQUIREMENTS FOR INCREASED CHILLER SIZES

CHILLER SIZE (kW)	MINIMUM STORAGE (kW-hrs)	MAXIMUM STORAGE (kW-hrs)
0.495	4.05	4.05
0.500	3.50	4.55
0.600	2.50	5.45

#### STORAGE SELECTION (EQUIPMENT)

Unfortunately, merely specifying the kWhrs (ton hrs) does not adequately describe the amount of storage equipment required for a particular application. The actual equipment selection must be capable of supplying the required kWhrs (ton hrs) at the specified conditions and rates. All thermal storage tanks are heat exchange devices and their performance depends on parameters that apply to all heat exchanger, such as the temperatures of the entering and leaving fluids. The higher the coolant temperature required from storage, the more total capacity is typically available.

Additionally, the performance of ice-based thermal storage equipment usually depends on the amount of storage that has been depleted. As water changes from a solid to a liquid, its physical properties, including thermal conductivity, also change. The ability of a secondary coolant thermal storage device to meet a particular load at a specific temperature will gradually decrease as the storage is depleted.

Furthermore, the cooling load imposed on the storage device is rarely constant. In the typical partial storage application, the chiller is constantly loaded during the design day and the storage handles the remaining, variable load.

This combination of variable loading and gradually diminishing performance usually requires a more detailed analysis in order to determine the worst case combination. Table 2 simulates the operation of the chiller and storage system as the design day progresses. It can be seen that the available temperature from the storage system reaches a maximum in hour 16. This is neither the maximum load hour, nor the hour of minimum ice inventory, but it is the hour where the combination of inventory depletion and load have combined for maximum impact on storage capacity. This worst case hour determines whether our equipment selection is capable of providing the kWhrs (ton hrs) at the proper conditions.

TABLE 2      SIMULATION OF STORAGE DISCHARGE (CHILLER UPSTREAM)

HOUR	TYPE	CHILLER EXIT TEMP (F)	REQUIRED STORAGE TEMP (F)	AVAILABLE MINIMUM TEMP (F)	RETURN TEMP (F)
8	P	44.8	43.0	32.1	51.1
9	P	46.0	43.0	32.3	52.2
10	P	47.2	43.0	32.7	53.4
11	P	47.7	43.0	33.2	54.0

12	P	49.5	43.0	35.2	55.7
13	P	50.6	43.0	37.1	56.8
14	P	51.8	43.0	39.6	58.0
15	P	50.6	43.0	40.3	56.8
16	P	49.5	43.0	41.4	55.7
17	P	44.3	43.0	40.8	50.5
18	P	43.1	43.0	40.7	49.3

Computer analysis simplifies this procedure, but it can be accomplished manually by accumulating the amount of ice discharged for each hour and comparing it to manufacturer's performance data as represented in attachment A. The calculations should be completed for at least the peak load hour and all subsequent hours of discharge. Usually, an initial estimate is made for the correct amount of storage (i.e. number of storage tanks), and the simulation is executed in order to determine if the estimate is adequate for each of the hours. The amount of storage is increased or decreased as necessary until the simulation either executes satisfactorily or fails to meet the requirements. The process is not as onerous as it first appears because accurate and complete performance charts make the initial selection reasonably accurate. This procedure also emphasizes why a specification of only kWhrs (ton-hours) or latent kWhrs (ton-hours) is inadequate to describe equipment performance. The appendix contains a complete simulation (Attachment B). This simulation is in the basic format suggested by ARI's Guideline T [1], a method for specifying the thermal performance of cool storage equipment.

Although the format of data presentation may differ, the design engineer should insist that all relevant parameters are represented. These include storage tank inlet and outlet temperatures, load and storage inventory.

#### OTHER ALTERNATIVES

Both the basic full and partial storage approaches have been calculated, but there are other alternatives that may be appropriate for a particular application. The utility rate structure often affects design decisions. In many parts of the



country, for instance, on-peak periods are condensed into 4 or 6 hour segments. In this case, designers often select a chiller large enough to meet any of the off-peak loads, even if they should occur during an occupied period, and then meet the entire on-peak load from storage. This often provides full storage benefits at a reasonable cost. This approach is useless without a properly structured utility rate.

Redundancy is also sometimes a concern of the designer. An option in this case is to operate two chillers in the ice-making mode and only one during the occupied or on-peak periods. If one chiller should fail, the other chiller is still available to make half of the normal compliment of storage and contribute to the load during the day. The demand avoidance is also increased beyond that available from the simpler pure partial storage method.

In calculating these alternatives the same procedure is used. The total cooling load is equated to the total contribution of the chiller, adjusted for each hour to account for its relative capacity. For the two chiller approach, for instance, the ice-making relative capacity (Icecap) could be set to 1.3 for each of the ice-making hours, assuming two chillers, each operating at 65% of its base, or datum, capacity. The daytime contribution (Day cap) would be set to 1 or 100% of its base rating. The result would equal the base rating for each of the two chillers.

This method of assigning relative capacities for the principal operating modes of the chiller, and assigning them to the appropriate hours, is useful for examining a wide variety of options. However, it is important to remember that the assumptions made regarding the operation of the chiller must be accurate representations of how the system will operate. If the assumption is made that the chiller will be operating at full load, but in practice the chiller actually unloads, the system sizing will be inadequate. An example of how this can occur will be discussed in a later section.

## SUMMARY OF EQUIPMENT SELECTIONS

In the preceding paragraphs a number of different options were analyzed and it might be helpful to summarize their important

features as well as the reasons one might be chosen over other alternatives. In Table 3 the first column represents the equipment sizing for the common and cost effective partial storage design. The chiller is approximately 45% of the peak load and the required storage is only about 40% of the total design day cooling load. Demand avoidance is limited to 55% of the peak cooling load but there is rarely a significant penalty in first cost.

Table 3 SUMMARY OF EQUIPMENT SELECTIONS  
(ALL KW'S ARE THERMAL)

	MINIMUM PARTIAL	FULL	2-CHILLER PARTIAL	4 HOUR ON- PEAK WINDOW
CHILLER kW	.445	.934	.603	.65
AVOIDED kW	.555	1.0	.699	1
STORAGE Kwhrs	4.05	8.5	5.49	5.92
% BACKUP	0	0	68	0

Full storage requirements are summarized in the second column. Of course, the entire chiller demand is avoided, however the chiller and storage sizing is more than doubled over partial storage.

The results for the 2-chiller option, described above, are presented in the third column. The chillers are approximately .3 kW each, with 5.5 kWhrs of storage capable of avoiding about 70% of the chiller related demand. If one of the chillers should fail, the system is still capable of supplying almost 70% of the total cooling capacity with no impact on our demand savings. Multiple chillers could also be selected for the partial and full storage methods, but the level of redundancy or demand savings will be reduced.

The last alternative discussed is for a situation where the utility on-peak period has been compressed into four hours. Although the chiller could be reduced to about .65 kW as represented in the table, designers will often select a chiller large enough to serve any load that occurs during the occupied, but off-peak, period. In this case, the chiller would then be .9 kW. About 6 kWhrs of storage will avoid all of the on-peak chiller demand, making this an attractive approach where

accommodated by the utility rate structure, such as parts of Florida, Texas and California.

In each of these cases, it is important to assign the correct capacity to the various chiller operating periods. This can sometimes be obscured by unusual load profiles. In rare cases, for instance, the calculated chiller can be larger than some of the actual loads. If our original assumption assumed a fully loaded chiller for that particular period, the chiller and storage selections will be incorrect. Properly executed computer analysis will adjust for these anomalies, however it is always recommended that the designer evaluate the control and operating logic for different operating periods and for a variety of loads.

## **APPLICATION**

### **SERIES ARRANGEMENT**

Thermal storage systems provide substantial flexibility in the ability to impose cooling load on either the chiller or storage. This flexibility, in turn, imposes added responsibility on the designer to insure that the equipment is being properly utilized. Premature storage depletion, as well as underutilized storage, result in lost demand savings or uncomfortable building occupants.

In the following discussions, a modulating valve that allows flow to bypass the storage equipment is assumed. This valve can adjust flow through storage in order to maintain assigned temperatures as well as prevent any discharge of storage when necessary. This is necessary because the temperature available from the storage device is variable, typically near 0C (32F) at the commencement of discharge and gradually increasing throughout the discharge period. If no blending valve were used, and the storage system was permitted to provide whatever temperature it was capable of, virtually all of the load could be imposed on storage and any planned contribution of the chiller would be absent.

In new installations the chiller and storage are often placed in series. This arrangement provides an effective and simple means of control. Assume that the chiller is upstream of storage. If

both the chiller and modulating valve control temperatures are set at the cooling supply temperature the chiller will be fully loaded before the storage can contribute to the load. This enforces control consistent with our partial storage selection assumption of a fully loaded chiller during the entire discharge period.

If, on the other hand, the chiller temperature setpoint were fixed at some intermediate value, storage would be compelled to provide at least a minimum contribution for every hour of load. It is up to the designer to determine if this is consistent with the original design intentions or the economically preferred method. On a design day, this control sequence may prematurely discharge storage, however during lower load periods of the year, it is an effective means of shifting a greater proportion of the load to storage and thereby further reducing on-peak demand. By controlling the specific temperature, or demand limiting the chiller, load can be proportioned between the two components in any ratio desired.

With the chiller downstream of storage, setting the storage modulating valve control temperature at the system supply temperature will completely deplete storage before the chiller will contribute to the load. This may be desirable during lower load periods when a full storage approach is possible and beneficial, but at other times will result in a totally inadequate cooling system. Once again, an intermediate value, either constant or variable, can be used to proportion load in any desired ratio.

Other variations in series system control are logical extensions of these discussions. In any case, the method of control must be consistent with our original equipment selection. It is further suggested that the method of control be evaluated at a variety of loads. A control scheme that operates satisfactorily at full load may be inadequate at part load. For instance, a particular chiller temperature setpoint may fully load a chiller at peak load, but as the return temperature falls with lower loads, the chiller may not operate at full capacity. This may or may not be advisable, but it is essential that it be consistent with our original design assumptions.

Series systems have other influences on our design. Because we are typically working with chillers that are approximately half

the size they would be in a conventional design, it is usually unfeasible to design with conventional system flow rates. For this reason it is common to expand the operating delta T's to 8 to 9C (14.4 to 16.2F). The resulting flow rate is usually acceptable for both the discharge and ice-making periods with delta T's in the ice-making mode of 2 to 4C (3.6 to 7.2F).

As discussed, the arrangement of components and control methodology are interrelated with our original equipment selection. This interdependence extends to other areas as well. By placing the chiller upstream of storage, its operating temperatures will be elevated, possibly altering our original estimate as to the relative chiller capacity. In this position, the storage, however, will be supplying lower temperatures and may have diminished capacity. This configuration was simulated in Table 2 where chiller leaving temperatures are 7.2C (45F) to 11.1C (52F) but the required storage temperature is 6.1C (43F).

If we reverse the component locations by placing the chiller downstream of storage, its capacity will be reduced but the storage capacity will be enhanced. Table 4 represents this approach where the chiller must now supply 6.1C (43F). The required temperature from storage has risen to 7.2C (49F) but the same storage equipment selection is still capable of the lower temperature. This indicates it would be possible to reduce storage sizing without affecting the ability of the system to meet all of the cooling loads. Once again, the system, in execution, must be consistent with the original design assumptions regarding chiller capacity and operating temperatures of the individual components.

TABLE 4 SIMULATION OF STORAGE DISCHARGE (CHILLER UPSTREAM)

HOUR	TYPE	CHILLER EXIT TEMP (F)	REQUIRED STORAGE TEMP (F)	AVAILABLE MINIMUM TEMP (F)	RETURN TEMP (F)
8	P	43.0	49.2	32.1	51.1
9	P	43.0	49.2	32.3	52.2
10	P	43.0	49.2	32.7	53.4
11	P	43.0	49.2	33.3	54.0
12	P	43.0	49.2	34.4	55.7
13	P	43.0	49.2	35.9	56.8

14	P	43.0	49.2	38.4	58.0
15	P	43.0	49.2	39.3	56.8
16	P	43.0	49.2	40.5	55.7
17	P	43.0	49.2	39.4	50.5
18	P	43.0	49.2	39.6	49.3

## PARALLEL ARRANGEMENT

Either due to engineering preference, or to preexisting conditions, a parallel equipment arrangement may be favored. Parallel arrangements are usually compatible with conventional system flow rates and delta T's. The parallel arrangement must revert to a series arrangement during the ice-making period when the storage becomes the load for the chiller.

In the parallel configuration both the chiller and storage have the same return (inlet) temperatures. As the return temperature varies with the system load, a constant chiller temperature setpoint will result in chiller unloading. In fact, using this control approach, the chiller and storage will assume partial loads in a constant proportion equal to that at full load. A chiller that provides 50% of the peak load will continue to supply 50% of part loads. Once again, this is not necessarily undesirable, but it must be consistent with the original design intention and sizing calculations. A wide variety of parallel arrangements are possible, each with advantages and disadvantages, but it is generally more difficult to attain the level of control flexibility possible in the series approach. Additionally, neither the chiller nor storage benefit from elevated operating temperatures.

## ICE-MAKING MODE

Chillers will typically be fully loaded during the ice-making process, and remain so until the storage is fully charged. There might appear to be some benefit in unloading a chiller while in this mode, however there are usually practical obstacles that prevent this option. Capacities are already reduced due to the depressed coolant temperatures. Further reductions in refrigerant flow usually cannot be comfortably accommodated by refrigerant control devices. Also, centrifugal chillers, which can be excellent ice-making machines, are forced

closer to their surge limits by unloading. In any case, the designer should consult with the chiller manufacturer if unloading of the chiller in the ice-making mode is contemplated.

Loads that occur during the ice-making period can be easily accommodated, providing some precautions are observed. Since coolant temperatures will be depressed, it may be advisable to include a means of recirculation on the load loop in order to temper the fluid temperature to more reasonable levels. This is absolutely imperative where heat exchangers are used to isolate the storage system from a conventional chilled water loop. A protective temperature sensor in the HX inlet is also advisable in case of control malfunction. This should be included whether or not a load during ice-making is anticipated.

If the load exceeds the ice-making capacity of the chiller, no ice will be made, as the chiller leaving temperature will rise until the machine capacity matches the load. If the night load exceeds 20 to 25% of the machine capacity, it is usually advisable to serve these loads with a separate machine operating at standard temperatures. This will be more efficient as well as operationally preferable. All night loads must be included in the original analysis if they are to be served by the storage system chiller.

## **SUMMARY**

In executing a thermal storage design, the proper consideration of all factors is essential to success.

The utility rate structure and building load profile will determine the proper scheduling of the different operating modes. The duration of the different operating modes affect the total capacity capabilities and requirements for both the storage and chiller.

The utility rate structure, as well as the availability of any incentives, will define the acceptable limits of equipment selection, i.e. partial or full storage. Although full storage will have greater demand and energy cost savings, the time to

recover the higher initial investment may be unacceptable unless the on-peak period is abbreviated or incentives help support the initial installation.

The relative position of the primary components affects the capacities of those components. The designer can choose to locate those components to either enhance chiller performance or storage capacity. Or, perhaps, some other arrangement will be necessary in order to conform to other system requirements such as flow rate limitations. Each of these configurations will have its own particular affect on equipment selection and control methodology.

It is essential that the control sequence be consistent with the assumptions made during our initial selection. Thermal storage provides a unique level of versatility in the approach to meeting the cooling loads. This versatility imposes an added responsibility to insure that the system operation is consistent with the original design intentions. The inadvertent shifting of load to either the storage or chiller can result in lost savings or poor comfort control. Proper anticipation of these possibilities includes analysis of the control sequence at a variety of different loads in addition to peak load.

Properly executed thermal storage designs have proven to be versatile and effective energy cost management tools. As in any HVAC system, the application and operation must be consistent with the design intentions.

## **REFERENCES**

1. 1994 Guideline for Specifying The Thermal Performance of Cool Storage Equipment, (Air-Conditioning and Refrigeration Institute, 1994).

### **AUTHOR'S ADDRESS**

Calmac Manufacturing Corp.  
101 West Sheffield Avenue  
Englewood, NJ 07631